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Abstract

Increasing emissions from road transport is a growing concern for planners and policy makers. Concurrently, congestion is another major issue which affects user behavior, escalates emissions and other externalities, and thus, reduces system welfare. Recent contributions in the literature investigated the interrelationship between congestion and emission levels, and find them to be positively correlated. However, most studies focus on pricing strategies to mitigate one isolated externality, and examine impacts on the other externality. This paper continues this line of research by investigating the effect of congestion pricing on emission levels, and the effect of emission pricing on congestion levels for a large-scale case study of Sioux Falls (South Dakota, US). Going beyond existing studies, the paper then proposes a joint optimization approach of internalizing both externalities simultaneously, and analyzes the effect of different available choice dimensions for users (route, mode, and departure time choice) on the results. The findings for separate pricing of the externalities are in line with the literature, and indicate a positive correlation between congestion and emissions. Furthermore, it is found that simultaneous pricing of congestion and emissions yields a higher increase in system welfare than separate pricing of only one externality. Mode choice turns out to be the determining factor of this welfare change, and therefore needs to be included in the transport model. Finally, the case study shows that simply combining the toll levels obtained from the separate pricing strategies will most likely result in tolls above the economic optimum, and thus, reduce overall welfare.

Keywords: Air Pollution, Congestion, Vehicle Emissions, Road Pricing, Simultaneous Pricing, Internalization, Agent-based Modeling

1 Introduction

Road congestion is a widespread phenomenon across the world and in particular present in metropolitan areas where travel demand is high and capacities are naturally limited by scarce urban space. The expected increase in traffic mainly resulting from urbanization processes is likely to increase negative externalities[1] such as road congestion, damage to the environment, and human health (see, e.g., Weinreich et al., 1998; Maibach et al., 2008). These externalities yield efficiency losses which can sum up to a significant part of a country's GDP (Gross Domestic Product). For example, a study by Creutzig and He (2009) indicates that the total external costs by motorized traffic in Beijing range between 7.5% and 15% of GDP. For the total external costs in the EU-27, Becker et al. (2012) find them to annually reach 373 billion EUR – equivalent to 3.0% of the region's GDP.

Congestion externalities occur, since every vehicle on the network imposes costs on other vehicles in terms of increased travel time. These costs are not compensated by any market mechanism, and are therefore not considered in people's decisions. The theory on time allocation suggests that an affected person explicitly loses *utility from travel time* which e.g. depends on comfort and pleasantness of the transport mode. Additionally, that person implicitly loses *time as a resource*, which could be used to perform a beneficial activity (Jara-Díaz, 2007; Börjesson and Eliasson, 2014).

Exhaust emission externalities occur, since vehicular traffic emits significant emission pollutants like carbon monoxide (CO), nitrogen oxides (NO_x), particular matter (PM), sulfur dioxide (SO_2) etc., which are the main components for polluting air and these in turn are responsible for adverse effects on health and living conditions. However, these adverse effects on others are typically not considered in people's mobility decisions.

In order to correct for these market failures, planners and policy makers may look for measures which reduce the efficiency loss caused by the negative externalities. One option in this context is to aim for behavioral changes of people which increase the efficiency of the system. From the economic literature it is known that internalizing external effects by a tax can increase overall welfare to society (Pigou, 1920). This lead to many studies

[1] 'Externality' will in this paper be used as a synonym of 'negative externality' unless otherwise stated.

on road pricing which all focus on finding the theoretically optimal tolls for road congestion (Lindsey and Verhoef, 2001; Small and Verhoef, 2007; Vickrey, 1969; Henderson, 1974; Arnott et al., 1993). However, there is only a limited number of contributions that aimed at finding optimal toll levels for emissions (see, e.g., Kickhöfer and Nagel, 2013) or for emissions and congestion simultaneously (see, e.g. Wang et al., 2014; Proost and van Dender, 2001). The former solve the problem using a simulation-based optimization for large-scale scenarios considering dynamic traffic flows. The latter use an analytical approach for a small six-node network, and a large-scale scenario of Brussels (Belgium) with static traffic flows, respectively. None of these studies attempted marginal social cost pricing for congestion *and* emissions in a large-scale scenario with dynamic traffic flows and activity-based demand.

More practically oriented contributions investigate the impact of various pricing strategies on congestion and emission levels (see, e.g. Beamon and Griffin, 1999; Daniel and Bekka, 2000; Proost and van Dender, 2001; Beevers and Carslaw, 2005; Namdeo and Mitchell, 2008; Barth and Boriboonsomsin, 2009). They all find that their pricing strategies will influence congestion patterns and emissions in the same direction. Hence, there is strong empirical evidence that these two externalities are positively correlated.

In the first step, the present study continues this line of research by investigating the effect of congestion pricing on emission levels, and the effect of emission pricing on congestion levels. For that purpose, the marginal congestion pricing approach by Kaddoura and Kickhöfer (2014) and the marginal emission pricing approach by Kickhöfer and Nagel (2013) are applied to Sioux Falls (South Dakota, US).

In the second step, the study extends the existing literature by applying a combined marginal social cost approach for automobile emissions and congestion. Because of the above correlation between congestion and emissions, the hypothesis is that *simply combining the toll levels obtained from the separate pricing strategies will result in tolls above the economic optimum*. Hence, the contribution of the combined approach is to determine individual vehicle-specific, time-dependent toll levels that include both externalities under consideration. Additionally, it is tested how much of the overall impact results from the possibility for travelers to change their mode, i.e. whether setting optimal car prices without considering the alternative mode is a valid approach for such policy design. The results are optimal emission-congestion levels for a particular case study. The methodology that is developed can, however, be applied to any scenario worldwide.

The remainder of the paper is organized as follows: Sec. 2 explains the transport simulation framework that is used for this study, and presents methodology of internalizing external congestion and emission effects within this framework. Sec. 3 presents the various scenarios in this study and their input parameters. Further, Sec. 4 demonstrates the comparison between different scenarios and various other results. Finally, Sec. 5 concludes the study by summarizing the main findings.

2 Methodology

2.1 MATSim

The multi-agent transport simulation MATSim[2] is used for all simulation runs. Detailed information about the software has been published e.g. by Balmer et al. (2009, 2005); Raney and Nagel (2004, 2006). The main idea of MATSim is to provide a framework for simulating transport in large-scale scenarios. Minimal inputs are network data, daily plans of individual travelers, and simulation configuration parameters. Every individual is considered as an agent who learns within an iterative process that is composed of following three steps:

1. **Plans Execution -** All selected plans are executed simultaneously using predefined mobility simulations. In this study, a state-of-the-art queuing model (Gawron, 1998; Cetin et al., 2003) is used.

2. **Plans Evaluation -** To compare various plans, executed plans are evaluated using a utility function. A plan's utility (V_{plan}) is represented by:

$$V_{plan} = \sum_{i=1}^{n} (V_{perf,i} + V_{travel,i}) \ , \tag{1}$$

where n is the number of activities, $V_{perf,i}$ is the utility from performing activity i and $V_{travel,i}$ is the (typically negative) utility for traveling to activity i. Utility earned for performing an activity following Charypar and Nagel (2005) is given by:

$$V_{perf,i}(t_{perf,i}) = \beta_{perf} \ . \ t_{*,i} \ . \ \ln(\frac{t_{perf,i}}{t_{0,i}}) \ , \tag{2}$$

[2] See `www.matsim.org`

where t_{perf} and t_* are the actual performed and typical duration of the activity, respectively. β_{perf} is the marginal utility of performing an activity at its typical duration which is the same for all activities, since in the equilibrium, all activities at their typical duration need to have the same marginal utility. $t_{0,i}$ is a scaling parameter that is related both to the minimum duration and to the importance of an activity. As long as dropping activities from the plan is not allowed, $t_{0,i}$ has essentially no effect. Mode-specific utility from traveling by car or public transport (PT) following Kickhöfer et al. (2013) is given by:

$$\begin{aligned} V_{car,i} &= \quad \beta_{tr,car} \,.\, t_{i,car} + \beta_c \,.c_{i,car} \\ V_{pt,i} &= \beta_0 + \beta_{tr,pt} \,.\, t_{i,pt} + \beta_c \,.c_{i,pt} \ , \end{aligned} \tag{3}$$

where t_i is the travel time of a trip to activity i and c_i is the corresponding monetary cost. Travel times and monetary costs dependent on travel mode as indicated by the indices ('car' and 'pt'). The behavioral parameters (β_{perf}, $\beta_{tr,car}$, $\beta_{tr,pt}$ and β_c) used in the present study are listed in Tab. 1. β_0 is an alternative specific constant which is in present study set to zero during base case set up (see Sec. 3.2).

3. **Re-planning -** For the next iteration, a new plan is generated for some of the agents by modifying an existing plan's attributes. These modifications are performed by software modules that can be defined arbitrarily. The most common modules change the route, departure time, or mode of a trip.

By repeatedly performing the steps from above, an iterative process is initiated which finally results in stabilized simulation outputs.

Table 1: Utility parameters used for all simulation runs. Source: Kaddoura et al. (2015).

Parameter	Value	Unit
Marginal utility of monetary cost (β_c)	− 0.062	utils/EUR
Marginal utility of performing (β_{perf})	+ 0.96	utils/h
Marginal utility of traveling by car ($\beta_{tr,car}$)	− 0.00	utils/h
Marginal utility of traveling by PT ($\beta_{tr,pt}$)	− 0.18	utils/h
Value of Travel Time Savings car ($VTTS_{car}$)	15.48	EUR/h
Value of Travel Time Savings PT ($VTTS_{pt}$)	18.39	EUR/h

2.2 Emission pricing

The emission modeling tool was developed by Hülsmann et al. (2011) and further improved and extended by Kickhöfer et al. (2013). This tool is used along with the MATSim framework. Currently, emissions are calculated for free flow and stop&go traffic states. Emissions consist of cold emissions (during warm up phase of vehicle) and warm emissions (while driving); cold emissions essentially depend on parking duration, distance traveled, and vehicle characteristics; warm emissions depend on engine type, road category, and speed of the vehicle. Thus, cold and warm emissions for each agent on each link are calculated using the HBEFA[3] database.

Furthermore, Kickhöfer and Nagel (2013) developed a method to calculate time-dependent, vehicle-specific emission tolls. In this method, person and link-specific time-dependent emissions are converted into monetary units (emissions costs) using emission cost factors given in Tab. 2. In the simulation, every time an agent leaves a link, the agent consequently pays the monetary equivalent of the produced emissions. Within the iterative learning cycle (see Sec. 2.1), the agents learn how to react on these individual tolls, and might change their behavior accordingly. This is referred to a internalizing the external emission effect (see later in Sec. 2.4).

Table 2: Emission cost factors. Source: Maibach et al. (2008).

Emission type	Cost factor (EUR/ton)
CO_2	70
$NMHC$	1700
NO_x	9600
PM	384500
SO_2	11000

2.3 Congestion pricing

The framework to compute individual delays and then to internalize those by a marginal social cost pricing scheme in an agent-based simulation is provided by Kaddoura and Kickhöfer (2014). This tool is also used along with the MATSim framework. Route and

[3] 'Handbook Emission Factors for Road Transport', Version 3.1, see `www.hbefa.net`

travel time tracking of all agents provides the dis-aggregated delays[4] and allows to identify the delay causing agents. The latter can therefore be charged with the equivalent monetary amount of the delays they caused for other agents. Since congestion is – in contrast to emissions – inherent to road traffic, the behavioral parameters from Tab. 1 can directly be used to convert delays into monetary units. This is done using the Value of Travel Time Savings (VTTS) of the car mode.[5] Again, the monetary payments are considered in the utility-based learning cycle of MATSim, and, hence, the external congestion effect is internalized.

2.4 Internalization

Internalization is the process by which external costs are included into the behavioral decision making of individuals by setting prices for these effects. At first, the MATSim utility functions only incorporate marginal private costs (MPC) which correspond to spending time and money for traveling to planned activities (see Eq. 1 and Eq. 3). Marginal social costs (MSC) can be called as sum of MPC and marginal external costs (MEC) (see, e.g. Walters, 1961; Turvey, 1963). The external component can result from any of the externalities mentioned in Sec. 1. This study attempts to compute MEC for different scenarios listed in Tab. 3, and then set prices accordingly in order to improve the efficiency of the transport system. In the Base case and the "Business As Usual" (BAU) scenario, no externalities are internalized. Thus, utility from traveling to an activity is given by Eq. 3. For all other scenarios, the price of emissions and/or congestion is added to the overall utility of every trip. When internalizing emission and congestion of car traffic jointly (ECI), the utility of traveling to an activity is given by:

$$V_{car,i} = \beta_{tr,car} \cdot t_{i,car} + \beta_c \cdot (c_{i,car} + c_{emission,i} + c_{congestion,i}) \ , \tag{4}$$

where c_i are the MPC related to car use (fuel, potentially insurance and tax); and $c_{emission,i}$ and $c_{congestion,i}$ represent the monetary equivalents of the respective external effect of that trip on society obtained by the methodology from Sec. 2.2 and Sec. 2.3, respectively.

[4] Delay is in this study defined by the difference between the actual travel time on a link and the link's free flow travel time. That is, delays are calculated on a per-link basis and not for entire routes.

[5] The VTTS is definded as the individual willingness-to-pay for reducing the travel time by one hour. For a linear utility functions, it is the ratio of the marginal utility of travel time and the marginal utility of monetary cost. As mentioned earlier, the former is the sum of the disutility for traveling (β_{tr}) and the negative utility of time as a resource ($-\beta_{perf}$).

3 Case study

3.1 Inputs

To see the impacts of various internalization schemes, the well-known scenario of Sioux Falls city, South Dakota, United States, is chosen. It has been introduced by LeBlanc et al. (1975), and has just recently been converted into a MATSim scenario by Chakirov and Fourie (2014). Their initial population consists of 84'110 agents, each with one plan; 78.18% of the agents use car and the rest use PT. In the present study, only car mode is considered when computing emission and congestion externalities. PT travelers are teleported between activity locations and travel time for traveling between these activities is the product of free speed car travel time between activity locations and configurable teleportation mode specific factor.

Detailed raw road network for Sioux Falls is taken from OSM[6] and then converted into the MATSim XML format. It contains 5'032 nodes and 13'550 links (see Fig. 1). Important behavioral parameters are listed in Tab. 1.

3.2 Base case set up

Initially, a base case is set up by running the simulation for 500 iterations to stabilize travel demand. This is done by setting all alternating specific constants to zero, and thereafter varying the teleportation speed factor for PT in order to match the initial modal split distribution over distance from Chakirov and Fourie (2014).[7] The result of this calibration exercise is a teleportation speed factor of 2.65, which means that traveling by PT takes 2.65 times as long as traveling by car in an empty network.

3.3 Policy scenarios

Four policy scenarios (Tab. 3) are then simulated with different available choice dimensions: (1) mode choice enabled (MCE) and (2) mode choice disabled (MCD). The selected plans from the final iteration of base case are then reused in all scenarios as input plans. Each policy scenario is run for 500 iterations. For 80% of the iterations, agents are allowed to switch route, mutate departure time, and change travel mode, each with a re-planning

[6] Open Street Map, see `http://www.openstreetmap.org`

[7] The initial modal split (car : PT) was 78.18 : 21.82; the modal split after calibration is 79.66 : 20.34.

Figure 1: Sioux Falls network. Source: `www.openstreetmap.org` (© OpenStreetMap contributors).

probability of 10%. The rest of the agents chose plans according to a multinomial logit model. After 80% of the iterations, all agents chose plans from their generated choice set according to a multinomial logit model. As described in Sec. 2.4, different user-specific external costs are internalized for the scenarios listed in Tab. 3. PT is assumed to run emission free and as a without capacity constraints. Therefore, there is no emission and congestion externality for PT. Emission costs, congestion costs and toll payments for all four scenarios are computed.

Emissions costs Time-dependent and person-specific cold and warm emissions are calculated as described in Sec. 2.2. These emissions are then transformed into monetary units using emissions costs factors (see Tab. 2). These monetary emissions costs are summed up to get total emissions costs in each scenario.

Congestion costs As illustrated in Sec. 2.3, dis-aggregated delays are calculated for each causing agent and then converted into monetary units using the VTTS. Afterwards, these values are summed up to get the total congestion costs for each scenario. Additionally, and in order to perform welfare analysis, user benefits are calculated by converting the utility of selected plans of each agent into monetary terms (for the methodology of converting individual utility levels into money terms for project assessment, see Kickhöfer, 2014). Congestion costs and the negative perception of toll payments are both part of user benefits. Consequently, changes in social welfare is defined as the algebraic sum of changes in emission costs, toll payments, and user benefits. That is, toll payments are simply a transfer payment from users to some public authority. In the following, results of BAU, EI, CI and ECI are compared and discussed.

Table 3: Policy scenarios

Scenario	**Internalization method**
Business As Usual (BAU)	none
Emissions Internalization (EI)	see Sec. 2.2
Congestion Internalization (CI)	see Sec. 2.3
Emissions and Congestion Internalization (ECI)	see Sec. 2.2 and Sec. 2.3

4 Results

The results obtained from comparing the policy scenarios with respect to the BAU scenario are shown in Tab. 4. It depicts changes in emissions costs, delays costs, user benefits, and system welfare. Additionally, Tab. 5 provides insights into the modal shift induced by the different policies. The analysis is composed of two steps: First, in Sec. 4.1, the left column of the results is discussed where users can – in addition to departure time choice and route choice – also change transport mode. Second, in Sec. 4.2, the right column of the results is discussed where mode choice is not available for agents when reacting to the pricing schemes. The idea behind this comparison is (i) to investigate how the internalization of one externality influences the other externality, and (ii) to test the hypothesis whether the correlation between the two externalities in the combined internalization (ECI) yields toll levels that are lower than the algebraic sum of the toll levels from the individual internalization models. Additionally, it is analyzed how much of the overall impact results from the possibility for travelers to change mode, i.e. whether setting optimal car prices without considering the alternative mode is a valid approach for such policy design.

Table 4: Change in emissions, delays, welfare for all scenarios with respect to BAU

Mode choice	enabled (MCE)			disabled (MCD)		
Scenario	EI	CI	ECI	EI	CI	ECI
Change in emissions costs	-8.27%	-0.71%	-9.40%	-0.07%	-0.12%	-0.18%
Change in delays costs	-15.42%	-60.55%	-81.33%	-4.63%	-34.49%	-34.13%
Toll payments	9138.02	3426.81	10648.35	9899.37	1189.55	11083.9
Change in user benefits	-0.026%	0.003%	-0.016%	-0.030%	-0.002%	-0.033%
Change in system welfare	0.005%	0.014%	0.020%	0.000%	0.001%	0.001%

Table 5: Modal split

Initial Plans	78.18 (car)		21.82 (PT)	
Base Case	79.66 (car)		20.34 (PT)	
Mode choice	enabled (MCE)		disabled (MCD)	
Travel Modes	car	PT	car	PT
BAU	79.71	20.29		
EI	73.42	26.58	79.66	20.34
CI	79.38	20.61		
ECI	72.88	27.12		

4.1 Mode choice enabled

In the BAU scenario, absolute emission costs amount to 9961.92 EUR. Congestion costs sum up to 8715.16 EUR. That is, in the Sioux Falls scenario, emission and congestion costs are roughly at the same level. This is not in line with estimates from the literature where congestion costs represent a major part of the total external effects of road traffic (see, e.g., Maibach et al., 2008; Parry and Small, 2005). This indicates that the demand by Chakirov and Fourie (2014) combined with the network from OSM (and also with their initial network) is unlikely to represent real-world conditions. Hence, testing the approach in a real-world setup seems to be an important step after the present study. However, given the artificial structure of the current setup, it is still suitable in order to test the proposed internalization strategies. Only the interpretation of the exact figures needs to be done carefully. The main findings for the MCE case studies are:

- For EI, CI and ECI scenario, reductions in emission costs are 8.27%, 0.71%, and 9.4% respectively. That is, the combined approach yields the highest reductions in emission costs, closely followed by a pure emission cost internalization. Internalizing congestion, however, does not substantially reduces emissions.

- For the same strategies, reductions in delays costs are 15.42%, 60.55%, and 81.33% respectively.[8] Again, the combined approach yields the highest reductions of delay costs, followed by a pure congestion cost internalization. Internalizing emissions (EI) also reduces congestion to some extend, which supports the findings by Kickhöfer and Nagel (2013).

- User benefits in case of EI and ECI decrease because users are paying more toll than they gain from reductions in emissions and delays. Interestingly, this is not the case in the CI scenario, where users gain more in terms of utility than they pay in terms of tolls. That is, a pure congestion internalization yields a positive effect on society *before* considering additional benefits that could evolve from investing the toll payments in a meaningful way.

- System welfare is highest in the ECI scenario where, emission costs and delay costs are least among the four scenarios. Clearly, simultaneous pricing produces better results with respect to the reduction of total externalities.

- The sum of toll payments for the separate pricing strategies is higher than for the simultaneous pricing strategy. This supports the original hypothesis.

- More users shift their travel modes in EI and ECI than for CI (see Tab. 5). This means that pricing emissions results – for the current setup – in a strong modal shift

[8] Compared to the changes in emission costs, these numbers seem rather high. This is, however, due to the fact that delays can actually be avoided (e.g. by shifting enough individuals to PT or to different departure times), whereas emission costs can only be avoided by shifting *all* individuals to PT, or by changing completely to zero emission vehicles which is not considered in this study.

towards PT. In contrast, pricing congestion seems to shift people rather to different departure periods. This can be observed in Fig. 4a where emissions are increased in early and later hours of the day. Also, this is supported by Fig. 2a, where for CI (green line with '+'), the number of trips of non-peak hour activity end timesrises more importantly than for EI and ECI (red and yellow lines with '+').

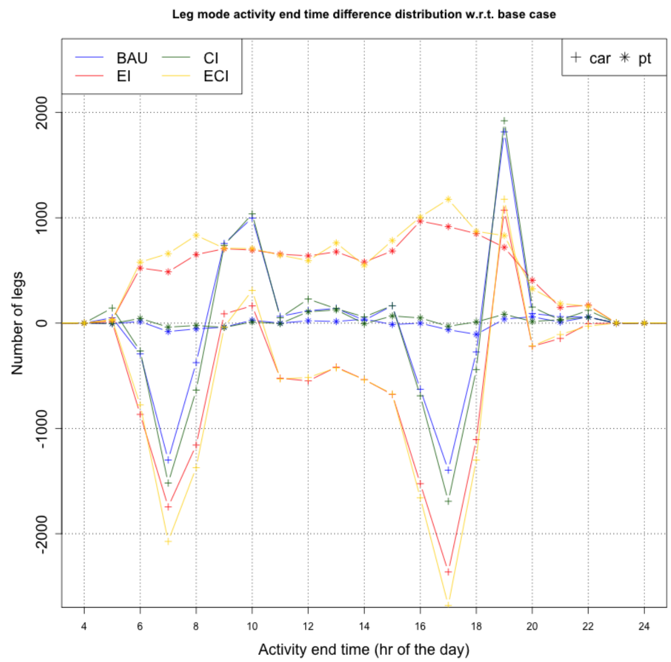
4.2 Mode choice disabled

In the BAU scenario, absolute emission costs amount to 9905.95 EUR. Congestion costs sum up to 1825.56 EUR. Again, emission costs being more important than congestion costs indicates that the scenario setup is not reflecting real-world conditions. Congestion costs in BAU scenario of MCE (8715.16 EUR) are significantly higher than in BAU scenario of MCD (1825.56 EUR) even though car shares for these two scenarios (79.71% and 79.66%) are not too different. This substantial difference in congestion costs is because of a rise in the number of car trips after turning off plans innovation in BAU scenario of MCE.[9] Thus, average travel time soars for car trips. Clearly, after turning off plans innovation, car trips are more attractive than PT. Also, it is noticed that in BAU scenario of MCD, trips with shorter travel time increased and trips with longer travel time decreased with respect to base case, unlike in BAU scenario of MCE. In consequence, congestion costs in BAU scenario of MCE is significantly higher than in MCD. The main findings for the MCD case studies are:

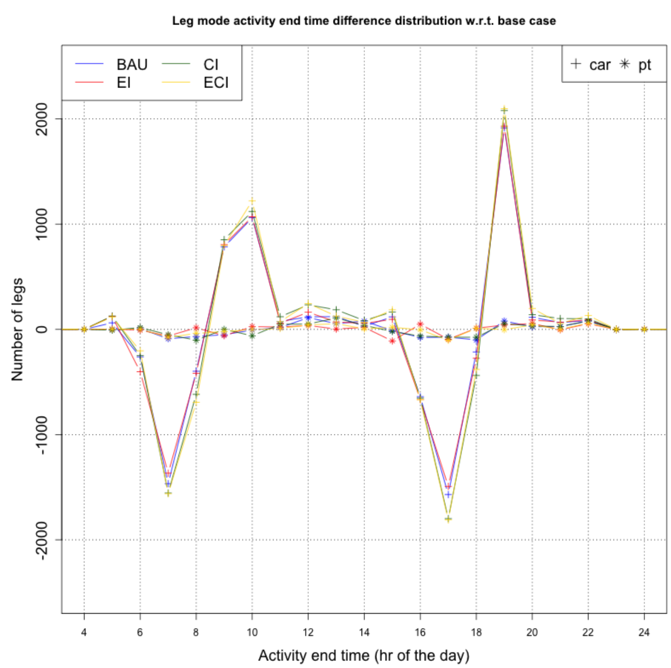
- For EI, CI, and ECI scenario, reductions in emission costs are 0.07%, 0.12%, and 0.18%. The combined internalization approach again yields the highest reductions, even though the overall reduction is rather weak compared to the MCE scenarios from above. It highlights the fact that the biggest part of emission reductions can be obtained by shifting travel mode to PT. Consequently, limiting the available choice dimensions to departure time and route choice only yields very inelastic demand when pricing emissions (missing substitutes). Hence, the pricing strategy does not seem very promising.

- For the same strategies, congestion costs are reduced by 4.63%, 34.49% and 34.13%,

[9] After 900 iterations, 22'142 agents have PT as travel mode in their selected plan and after 1000 iterations, such plans are only 17'069.



(a) MCE



(b) MCD

Figure 2: Leg mode activity end time difference distribution with respect to base case

respectively. Again, the reductions are lower than for the MCE scenarios but are still significant. This means that price elasticities of demand are also more inelastic than in the MCE cases, but time mutation and route choice still allow for improvements in the transport system. See Fig. 2b, where peak hour activity end times are reduced and non-peak hours activity end times are increased; also in Fig. 4b, where emissions are increased in non-peak hours due to shift in travel demand to non-peak hours. Since initial emission costs are five times higher than congestion costs, reducing emissions is dominating the choices of individuals in the combined internalization (ECI).

- The Sioux Falls network does not offer many routes that differ substantially in terms of distance (see Fig. 3). Only few trips are shifted from longer routes to shorter routes or vice versa.

- The change in user benefits is negative for the all three scenarios, since users are losing more from the toll payments than they gain from reduced travel times. In consequence, system welfare remains almost same as in BAU for all three strategies. Again, this is due to the fact that the MCD models lack in real alternatives for users. Pricing in a constraint environment without offering substitutes is typically not improving the efficiency of the system (see, e.g., Daniel and Bekka, 2000, who show that the smaller the demand elasticity the lower the potential welfare gain from pricing strategies).

- The algebraic sum of toll payments for the separate pricing strategies is almost equal to the toll payments for the simultaneous pricing. This would mean that the initial hypothesis needs to be rejected. However, this is likely to be related to the above argument of pricing strategies to be ineffective in constraint environments.

5 Conclusion

This paper applied an agent-based emission internalization strategy developed by Kickhöfer and Nagel (2013), and an agent-based congestion internalization strategy developed by Kaddoura and Kickhöfer (2014) to Sioux Falls (South Dakota, US). It was investigated how the internalization of one externality affects the other externality, and how the respec-

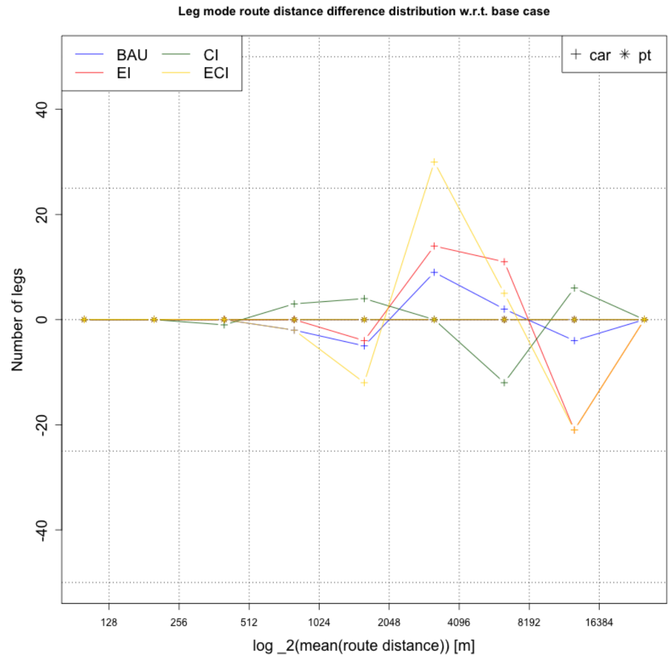
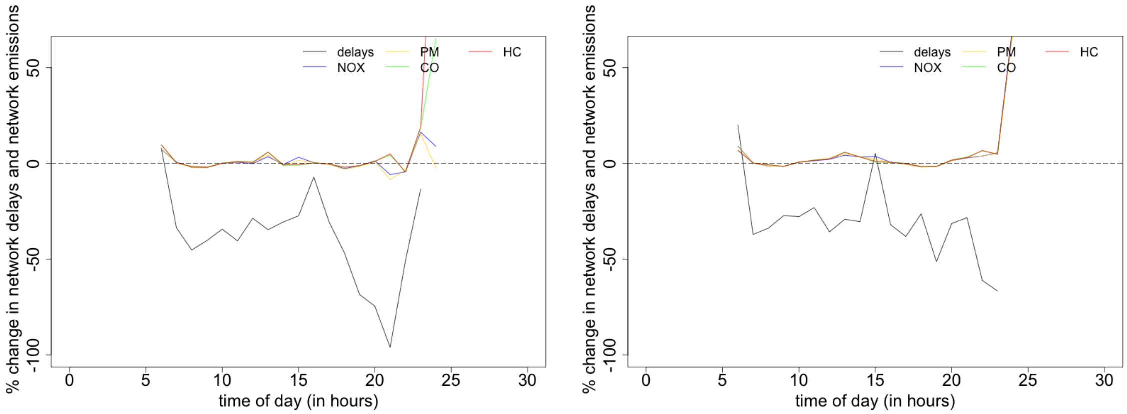


Figure 3: Leg mode route distance difference distribution for MCD

tive pricing mechanism influences user benefits and social welfare when users can react by changing their departure times and routes (MCD scenarios). Additionally, in the MCE scenarios, users were also allowed to change transport mode. The key findings for the separate internalization strategies are (i) that internalizing one externality has a positive impact on the reduction of the other externality (ii) that unlike internalizing emissions, internalizing congestion results in positive user welfare because utility gains (by reduction in travel time) are over-compensating toll payments (iii) that internalizing externalities improves system welfare only if demand is elastic enough.

The paper then extended the existing literature by running a simultaneous internalization strategy for emissions and congestion (ECI). The hypothesis was that optimal toll levels from the ECI strategy are lower than the algebraic sum of the individual optimization models (EI and CI) because emissions and congestion are to some extend correlated. The key findings for simultaneous internalization strategies are (i) that internalizing emissions and congestion results in least emission and congestion levels even when demand is inelastic (ii) that, in consequence, this strategy provides the strongest in system welfare (iii) that the algebraic sum of toll payments from EI and CI is higher than those of ECI; in consequence simply combining the toll levels obtained from EI and CI will most likely



(a) CI of MCE

(b) CI of MCD

Figure 4: Hourly % change in emissions and congestion for CI scenarios on Sioux Falls network

result in tolls above the economic optimum, and thus, reduce overall welfare.

Overall, it can be concluded that with the methodology developed in this paper, efficient prices for negative externalities in urban areas can be derived. The approach also proved to be applicable for a large-scale scenario, and it can therefore be used to create benchmarks when evaluating the effects of real-world policies. The setup of the Sioux Falls scenario, however, seems rather artificial. Travel demand consists mainly of local traffic which results in a rather uncongested network (especially on the major tangential motorways), and price elasticities of demand are dominated by mode choice. It therefore seems important to test the methodology in further studies with real-world scenarios. Additionally, pricing emission *exposure* rather than emissions similar to Kickhöfer and Kern (2014) seems promising, since toll levels then additionally depend on the number of affected individuals. This could potentially influence the price elasticity of emissions, since routing would – in such setup – offer more possibilities to reduce emission tolls than in the current setup with flat tolls per gram of pollutant.

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